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Long-Term Monitoring of Anomalous X-ray Pulsars

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Abstract. We report on long-term monitoring of anomalous X-ray pulsars (AXPs) using the *Rossi X-ray Timing Explorer*. Using phase-coherent timing, we find a wide variety of behaviors among the sources, ranging from high stability (in 1E 2259.1+586 and 4U 0142+61), to instabilities so severe that phase-coherent timing is not possible (in 1E 1048.1–5937). We note a correlation in which timing stability in AXPs decreases with increasing $\dot{\nu}$. The timing stability of soft gamma repeaters in quiescence is consistent with this trend, which is similar to one seen in radio pulsars. We consider high signal-to-noise ratio average pulse profiles as a function of energy for each AXP, and find a variety of behaviors. We find no large variability in pulse morphology nor in pulsed flux as a function of time.

1. Introduction

Anomalous X-ray pulsars (AXPs) are an unusual class of astrophysical objects. There are currently only five confirmed AXPs: 4U 0142+61, 1E 1048.1–5937, 1E 1841–045, RXS J170849.0–400910, and 1E 2259.1+586. All five are found in the plane of the Galaxy; and two of the five certain members of the class appear to be located at the geometric centers of apparent supernova remnants.

AXP characteristics can be summarized as follows (see Israel, Mereghetti, & Stella 2002, for a review): they exhibit X-ray pulsations in the range ∼5–12 s; they have pulsed X-ray luminosities in the range $\sim 10^{34} - 10^{35}$ erg s^{-1}; they spin down regularly; their X-ray luminosities are much greater than the rate of loss of rotational kinetic energy inferred from the observed spin-down; they have spectra that are characterized by thermal emission of $kT \sim 0.4$ keV with evidence for a hard tail in some sources. Soft gamma repeaters also exhibit AXP-like pulsations in quiescence (e.g. Kouveliotou et al. 1998); the connection between AXPs and SGRs is intriguing but not yet clear. The results here summarize those reported by Gavriil & Kaspi (2001).

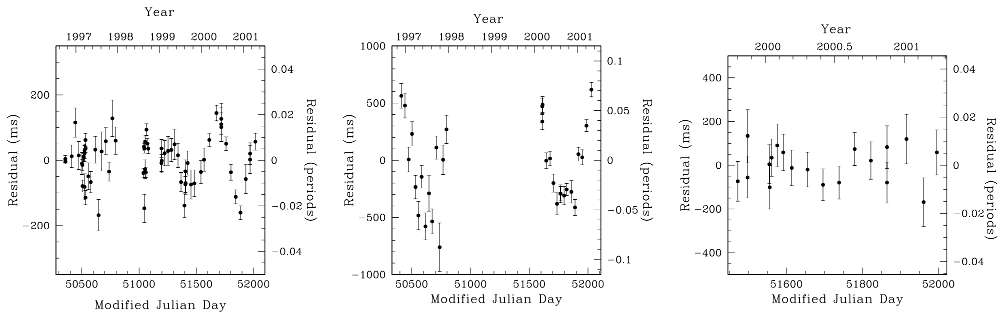

Figure 1. Left: Arrival time residuals for 1E 2259.1+586 with ν, $\dot{\nu}$ and $\ddot{\nu}$ subtracted; Center: Arrival time residuals for 4U 0142+61 with ν and $\dot{\nu}$ subtracted; Right: Arrival time residuals for RXS J170849.0–400910 with ν, $\dot{\nu}$ and $\ddot{\nu}$ subtracted.

2. Results and Discussion

The results presented here were obtained using the Proportional Counter Array (PCA) on board the Rossi X-ray Timing Explorer (*RXTE*). Our observations consist primarily of short snapshots taken on a monthly basis. In addition, we used a handful of archival observations; the exposures in these observations vary.

Phase-coherent timing of AXPs has shown that the rotational stability of some AXPs is comparable to those of some radio pulsars. The rotational stability of 1E 2259.1+586, first reported by Kaspi, Chakrabarty, & Steinberger (1999), has now persisted over 4.5 yr, although the inclusion of $\ddot{\nu}$ has recently been necessary. 4U 0142+61 has been an extremely stable rotator over 4.4 yr of *RXTE* monitoring. For RXS J170849.0–400910, phase coherent timing has been accomplished in the 1.4 yr since the glitch reported by Kaspi, Lackey, & Chakrabarty (2000). In these data, we find a significant positive $\ddot{\nu}$. This indicates a decay of the negative $\dot{\nu}$, expected for long-term glitch recovery, as seen in glitching radio pulsars (e.g. Shemar & Lyne 1996). 1E 1841–045 shows rotational stability but with considerably higher red noise (see Gotthelf et al., this volume). 1E 1048.1–5937 has exhibited far noisier behavior, making phase-coherent timing using monthly and weekly observations virtually impossible. Interestingly there is a correlation between timing stability and $\dot{\nu}$: the sources with the smallest $\dot{\nu}$ are the most stable. Arrival time residuals for 1E 2259.1+586, 4U 0142+61 and RXS J170849.0–400910 are shown in Figure 1.

AXP spectra are generally best fit by a two-component model consisting of a photoelectrically absorbed blackbody with a hard power-law tail (Israel et al. 1999). Whether these two components are physically distinct is an open question (see Özel, Psaltis, & Kaspi 2001). To investigate this, we compared the pulse profile morphology of the AXPs in two energy bands. Figure 2 displays the average pulse profiles of RXS J170849.0–400910, 1E 2259.1+586 and 1E 1048.1–5937 in the energy bands 2–4 keV and 6–8 keV. From Figure 2 it is clear that AXP pulse profiles exhibit different degrees of energy dependence;

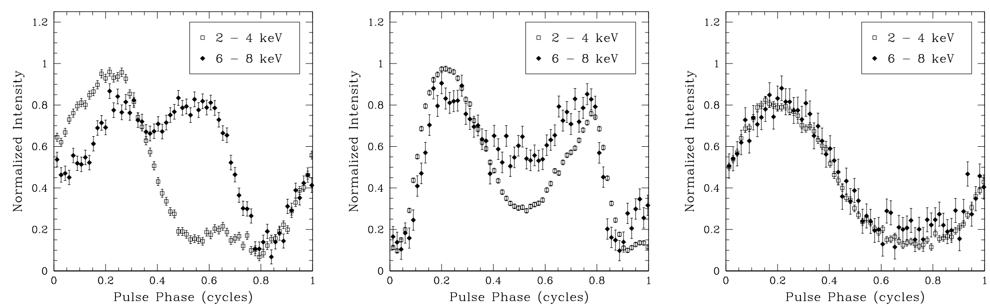

Figure 2. Average pulse profile of RXS J170849.0–400910 (left), 1E 2259.1+586 (center) and 1E 1048.1–5937 (right) in two energy bands. Note that the scaling was chosen to minimize the χ^2 of the difference between the two profiles. Thus the only information that these plots convey is the relative amplitudes of the features of the profile.

RXS J170849.0–400910 shows high energy dependence, while 1E 1048.1–5937 shows no energy dependence.

We have also used our *RXTE* data to monitor the pulsed flux of the AXPs as a function of time. Rapid (< months) flux variability would challenge the magnetar model and accreting sources generally show flux variability correlated with $\dot{\nu}$. Given the large field-of-view of the PCA and the low count rates for the sources relative to the background, total flux measurements are difficult with our *RXTE* data. Instead, we have determined the pulsed component of the flux, by using the off-pulse emission as a background estimator. The flux time series for 1E 2259.1+586, 4U 0142+61 and RXS J170849.0–400910 are displayed in Figure 3. We do not find evidence for any large variability in the pulsed flux for any source, and have set 1σ upper limits on variations ∼20–30% (depending on the source). This is surprising given previous reports of large (factor of 5–10) total flux variations in 1E 2259.1+586 and 4U 0142+61 (Baykal & Swank 1996; Oosterbroek et al. 1998). Assuming a constant pulsed fraction, this suggests that more than one of the AXPs happen to be much more quiescent during the *RXTE* monitoring than in the past.

Iwasawa, Koyama, & Halpern (1992) reported a significant change in the pulse morphology of 1E 2259.1+586 in 1.2–14 keV *GINGA* observations obtained in 1990, such that the leading pulse had amplitude roughly half that of the trailing pulse. If correct, this has important implications for the magnetar model, which predicts such pulse morphology changes in the event of a restructuring of the magnetic field, as might occur following a major SGR-like outburst. Motivated by this finding, we searched for pulse profile changes in our *RXTE* observations of all the AXPs. We have not detected any large pulse profile variations. This justifies our other analysis procedures which assume a fixed profile. We rule out variations in features having amplitude $\gtrsim$20% of the peak amplitude at the 1σ level, although the limit depends on source and integration time.

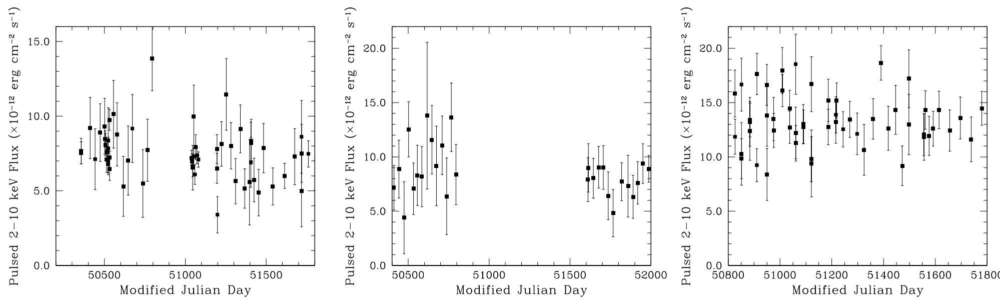

Figure 3. Pulsed flux time series for 1E 2259.1+586 (left), 4U 0142+61 (center) and RXS J170849.0–400910 (right). Error bars represent 1σ confidence intervals.

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